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# Measurements of Surface Waves radiated by a Vertically Polarized Antenna Over Planar Seawater at 5 MHz. Comparison to Planar Earth Models.

M. Bellec, S. Palud, P.Y. Jezequel, S. Avrillon, F. Colombel, Ph. Pouliguen

**Abstract**— High Frequency propagation over the surface of the Earth or sea is a relevant subject today, especially for High-Frequency Surface Wave Radars (HFSWR) over the horizon. In this paper, we present measurements of Electric field propagating over sea water in HF Band compared to K.A. Norton, R.W.P. King and G. Millington's theories, thanks to a reliable measurement setup. The transmitter antennas are located on the coast while the receiver antenna is installed on a boat which sails at constant azimuth. The Electric field measurements are carried out with a shielded loop antenna and we measured the field strength attenuation versus distance between the transmitter and the boat along a sea water path. In order to take into account the media change (the coast and the sea water), Millington's solution has been added to King's and Norton's theories with the planar Earth model. At 5 MHz over the sea water, the environment of propagation is an attractive feature for the trans-horizon radar application. Indeed, the attenuation along the path in the planar model is similar to the attenuation in free space but over the horizon. The measurements performed at 5 MHz and the calculations are in a good agreement.

**Keywords**— HF band measurements, surface-wave propagation, ground-wave field, vertical electric dipole, planar Earth model.

## I. INTRODUCTION

The surface waves propagation phenomenon presents attractive and useful features for industrial applications because the surface waves propagate along the surface of the Earth and beyond the radio-electric horizon. Thanks to these properties, the surface waves allow communication in hard environments (forest...) or target detection at very low elevation and at large distances. Furthermore, the temporal stability of the surface wave propagation is an attractive feature in a defense or civil context. Few examples already exist mainly operating in VLF, LF and in the HF band [1] [2].

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Introduced at the beginning of the last century, surface-wave propagation has been largely investigated starting by Sommerfeld [1] and followed by Norton [4] [5] and King [6] [7][8]. These pioneer researchers provided mainly theoretical studies and analytical solutions to this problem. Sommerfeld started by calculating the EM field radiated by an infinitesimal vertical electric dipole located on the surface of the planar Earth. Then, Norton introduced the attenuation function, the ground effect, and the frequency dependence of the surface wave radiated by a vertical dipole. Based on Maxwell's equations, R.W.P. King established the EM field expression generated by a vertical electric dipole placed on or in the vicinity of the surface of a planar Earth and described the surface-wave propagation behavior. King also introduced characteristic distances to explain the attenuation factor variation along the path. To introduce the environmental constraints, Millington developed an analytical method which takes into account the ground characteristics changes along the path [9]. All these studies are mainly theoretical and the measurements are unusual.

This paper presents the measurements of the surface waves over the sea at 5 MHz and gives the comparison between the experimental studies and the theoretical models provided in the literature, especially in order to validate the surface wave decrease as  $1/d$  all along the planar seawater path.

In this paper, we first present the surface-wave propagation theories proposed by Norton, King and Millington where the radiating element is a vertically polarized antenna located above the ground. In the second part, we present measurements performed over the sea. Firstly, the measurement process is carefully described including the design of the electrically small antenna used to radiate the surface waves. Secondly, we provide a comparison between the measurements and the theoretical results.

## II. PROPAGATION THEORIES

This section describes theoretical approaches and then provides an interpretation of the surface wave propagation theories on a planar Earth thanks to the research of Sommerfeld [1], K.A. Norton [5] and R.W.P. King [6] [7] [8]. These authors have provided electromagnetic field formulas radiated by an infinitesimal vertical electric dipole located at a specified height  $h_e$ , over an imperfectly conducting half-space. In this section, we have summarized these theories with a standardized notation system. We have employed a harmonic

time factor  $e^{-i\omega t}$  throughout. The infinitesimal dipole is fed by a unit electric

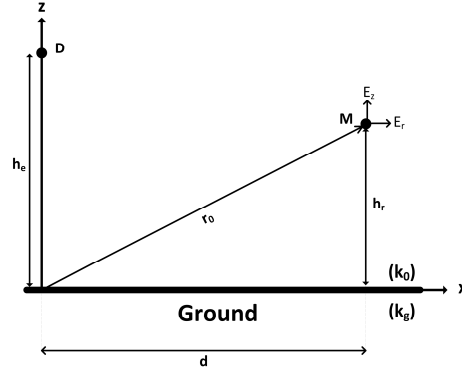


Fig. 1. Set of coordinates and location of an infinitesimal vertical electric dipole (D) at a height  $h_e$  in the air (wave number  $k_0$ ) over the ground (wave number  $k_g$ ).

moment  $Idl = I \cdot m$  (current  $I$ , infinitesimal length  $dl$ ).

Fig. 1 describes the set of coordinates and the geometry parameters. Since the propagation characteristics are dependent on ground properties, we use the wave numbers  $k_0$  and  $k_g$ , respectively in the air and in the ground, where  $\epsilon_{rg}$  and  $\sigma_g$  are respectively the relative permittivity and the conductivity of the ground. These media are assumed to have the same permeability  $\mu_0$  than free space.

$$k_0 = 2\pi/\lambda_0 \quad (1)$$

$$k_g = k_0 \sqrt{N} \quad (2)$$

$$N = \epsilon_{rg} + i\sigma_g/\omega\epsilon_0 \quad (3)$$

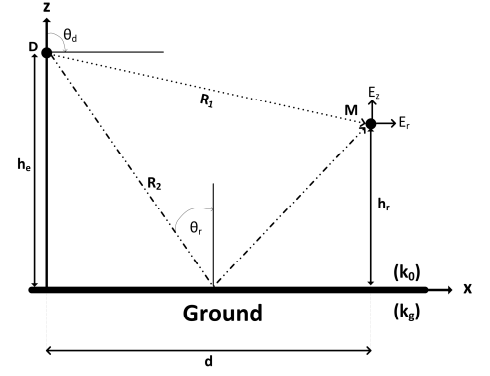
Where  $N$  is the complex refractive index of the ground.

#### A. Presentation of Norton's Model

The EM field radiated by an infinitesimal vertical electric dipole on the surface of the planar Earth was firstly analyzed by A. Sommerfeld [1]. Then, K.A. Norton simplified the calculation, the formalism and the interpretation [4][5] by introducing the attenuation function. Norton's formalism starts from the Hertz vector and Norton's model is valid whatever the transmitter or the receiver height. The Hertz vector expression  $\vec{\Pi}_z$  contains 3 terms: a direct wave, a reflected wave and the surface wave.

$$\vec{\Pi}_z = \frac{jZ_0 I l}{4\pi k_0} \left( \frac{e^{-jk_0 R_1}}{R_1} + R_v \frac{e^{-jk_0 R_2}}{R_2} + \frac{[1 + (1 - R_v)F(p)]e^{-jk_g R_2}}{R_2} \right) \vec{0} = -\frac{\mu_0}{2\pi} e^{ik_0 d} \left[ \frac{ik_0}{d} - \frac{k_0^2}{k_g} \sqrt{\frac{\pi}{k_0 d}} e^{-ip_0} \mathcal{F}(p_0) \right] \vec{0} \quad (4)$$

Where  $Z_0 = 120\pi$  is the free space impedance,  $R_v$  the Fresnel's



reflection coefficient and  $F$  the attenuation function of the surface wave.  $R_v$  and  $F(p)$  are defined with the following formula :

$$R_v = \frac{\cos\theta_r - \frac{k_0}{k_g} \sqrt{1 - \left(\frac{k_0}{k_g}\right)^2 \sin^2\theta_r}}{\cos\theta_r + \frac{k_0}{k_g} \sqrt{1 - \left(\frac{k_0}{k_g}\right)^2 \sin^2\theta_r}} \quad (5)$$

$$F(p_0) = 1 - \frac{(\pi p_0)^{\frac{1}{2}} e^{-p_0} \operatorname{erfc}(jp_0^{\frac{1}{2}})}{j} \quad (6)$$

Where  $p_0$  is the Sommerfeld numerical distance.

The relation between the magnetic field and the Hertz vector is:

$$\vec{H} = i\omega\epsilon_0 \operatorname{rot} \vec{\Pi}_z \quad (7)$$

#### B. Presentation of King's Model

R.W.P. King established the EM field expression generated by a vertical electric dipole located on or in the vicinity of the Earth surface from Maxwell's equations. According to [6], the transverse magnetic induction  $B_{2\phi}$  and associated electric field  $E_2$  are:

$$E_{2r}(d, z=0) = -\frac{\omega}{k_g} B_{2\Phi}(d, 0) \quad (9)$$

$$E_{2z}(d, z=0) = -\frac{\omega}{k_0} B_{2\Phi}(d, 0) \quad (10)$$

Where  $P_0 = k_0^3 d / 2k_g^2$  is the Sommerfeld numerical distance and  $F(P_0)$  is defined by the following formula:

$$\mathcal{F}(P_0) = \frac{1}{2}(1+i) - C_2(P_0) - iS_2(P_0) \quad (11)$$

Where,  $C_2(P_0) + iS_2(P_0)$  is the Fresnel integral and  $\omega$  is the pulsation.

These formulas have been proposed with the following conditions issued from [4] and [6] respectively:

$$|k_g|^2 \gg k_0^2 \quad \text{or} \quad |k_g| \geq 3k_0 \quad (12)$$

$$k_0 r_0 \geq 1, \quad r_0^2 \gg h_g^2, \quad k_0 r_0 \geq k_g h_g \quad (13)$$

Where,  $r_0$  is defined in Fig. 1.

The King's theory describes physically surface-wave propagation behavior by defining characteristic distances: the critical distance  $d_c$ , and the intermediate distance  $d_i$ . The critical distance  $d_c$  represents the boundary of the planar Earth model and the intermediate distance  $d_i$  is a baseline which defines the modification of attenuation law of the surface waves. Where  $a$  is the Earth radius.

$$d_c = a \left( k_0 a / 2 \right)^{-\frac{1}{3}} \quad (14)$$

$$d_i = \frac{2k_g^2}{k_0^3} \quad (15)$$

The critical distance  $d_c$  varies only with frequency, while the intermediate distance  $d_i$  varies both with frequency and the ground characteristics. There are two notions of horizon. First, the optical horizon which is close to 37 km at sea level. Secondly, in the field of surface-wave propagation, the radio-electrical horizon  $d_c$  which is the electrical planar Earth boundary. As well as the antenna dimensions, the electrical horizon depends on the wavelength.

As sketches in Fig. 2, we can distinguish two main areas of propagation behavior:

- Up to the intermediate distance  $d_i$ , the EM field decreases as  $1/d$ .
- Starting from  $d_i$ , the EM field decreases as  $1/d^2$ .

Physically, the transition between the two areas is smooth. We call this transition area the “smoothly” attenuation (dotted zone).

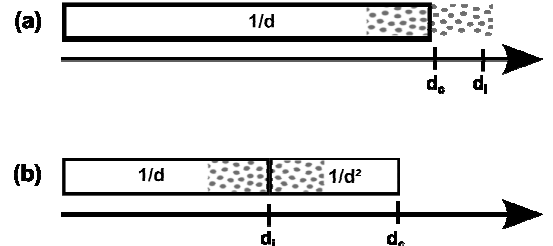


Fig. 2. Two main areas of propagation behavior around the “smoothly” area (dotted zone).

The trans-horizon radar application requires a long coverage (200 nmi). Even if the sea water is a favorable medium to the surface wave propagation, the frequency is an important choice relative to the characteristic distances ( $d_c$  and  $d_i$ ). The 5 MHz frequency is a special case (Fig. 2- a): the intermediate distance ( $d_i=270$  km) is superior to the critical distance ( $d_c=90$ km). Knowing that  $d_i > d_c$ , the surface wave propagation decreases as  $1/d$  all along the planar model range (90 km). This behavior is an attractive feature to the need of large coverage and detections at large distances.

### C. Millington's Model

The Millington's model is applied as soon as the environment contains several ground types along the propagation path. A simple case is sketched in Fig. 3 with two transitions through three media.

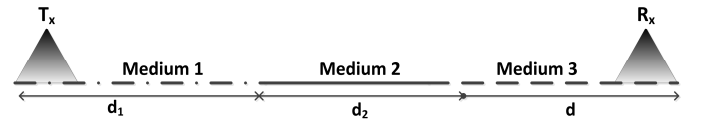


Fig. 3. Sketch of the Millington's model: The transmitting antenna ( $T_x$ ) is located over the medium 1 while the receiver antenna ( $R_x$ ) is located over the medium 3. The medium 1 represents a segment range of length  $d_1$ , the medium 2 represents a segment range of length  $d_2$  and the medium 3 represents a segment of a variable length  $d$ .

According to Fig. 3, the semi empirical method can be explained with the following equations (19)-(21) coming from [10] and [11]:

The total field  $E_T$  along a multi-mixed propagation path at the receiver is defined by:

$$E_T(d) = \frac{1}{2}(E_D(d) + E_R(d)) \quad (16)$$

Where  $E_D$  and  $E_R$  are respectively the fields along the direct and reverse paths:

$$E_D(d) = E_1(d_1) - E_2(d_1) + E_2(d_1 + d_2) - \quad (17)$$

$$E_R(d) = E_3(d) - E_2(d) + E_2(d_2 + d) - E_1(d_2 + d) + E_1(d_1 + d_2 + d) - E_1(d_1 + d_2) \quad (18)$$

Where  $E_1$ ,  $E_2$  and  $E_3$  are respectively the field over the medium 1, the medium 2 and the medium 3.

The Millington's method shows that the EM surface wave field strength is subject to the medium change. According to the modification of electrical ground characteristics, sea-ground or ground-sea, the EM field could respectively increase or decrease from each transition.

### III. MEASUREMENTS SETUP

#### 1) Global description

The goal of our measurements is to validate the 1/d attenuation of the surface waves at 5 MHz calculated with the planar Earth models. In this section, we present the measurement objectives and the setup used to measure the attenuation of the Electric field over the sea.

A transmitter has been designed at 5 MHz to check the theoretical propagation results:

- $d_c = 90$  km
- $d_i = 270$  km

No roughness parameter has been considered because the marine forecast was optimal (calm sea).

The experimentation took place at the Mediterranean Sea in October 2013. Fig. 4 depicts the path carried out over the sea. Transmitting HF antennas are located on the coast (Tx) and the received signals are carried out with loop antennas-installed on a boat (Rx). The boat followed a southwestward path across the Mediterranean Sea, steering a constant course. Each measurement was geo-localized and stored with an acquisition software developed by TDF. The transmitting antenna operating at 5 MHz is located over salt ponds. A mixed-path has also been considered (see Fig. 1):

- Salt ponds along 2 km
- Mudflat along 1 km
- Sea Water along 220 km

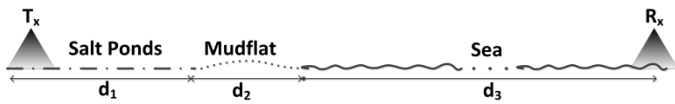


Fig. 1. Sketch of the experimental path: The transmitting antenna (Tx) is located over salt ponds while the receiver antenna (Rx) is located over the sea. The salt ponds represent a segment range of length  $d_1=2$  km, the mudflat represents a segment range of length  $d_2=1$  km and the sea represents a segment of a maximal length  $d_3=220$  km.

The relative permittivity  $\epsilon_{rg1}$  of the salt ponds is 80, and the conductivity  $\sigma_{g1}$  is 8.8 S/m. For the mudflat transition,  $\epsilon_{rg2}=50$  and  $\sigma_{g2}=0.4$  S/m. For the sea water,  $\epsilon_{rg2}=80$  and  $\sigma_{g2}=5$  S/m.

These  $E_1$  (conductivity) and  $E_2$  (layer) have been measured thanks to commercial devices:

- HANNA HI 993310 with HI 76305 probe for ground
- HANNA HI 9033 with HI 76302 probe for liquid

The measurements have been carried out in Continuous Waves (CW). Knowing that the transmitting antenna has a monopole shape radiation pattern, a preliminary study has been carried out in order to check the ionospheric activity using VOACAP software (HF Propagation Prediction and Ionospheric Communication Analysis). The Observed Sunspot Number during the measurement was 60. A minimal field strength difference of 30 dB at 90 km at 2 p.m. has been observed. This means that only one-thousandth of the received field strength could come from the sky waves. As a result, we assure that no ionospheric activity could disturb the surface electric field strength measurement.

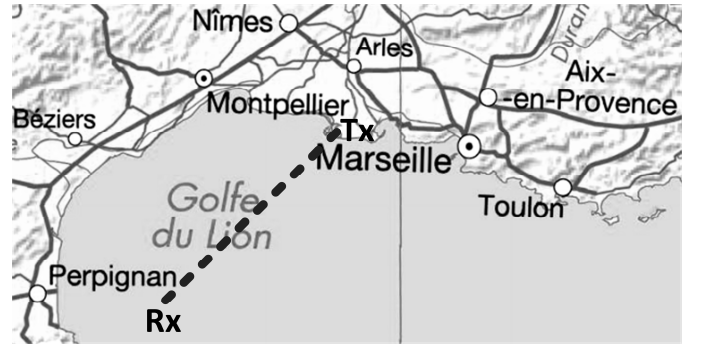


Fig. 4. Typical round of measurement over the sea by boat from the vicinity of the transmitter (Tx) until the receiver (Rx).

#### 2) Antennas used for the measurements

The measurement setup used two types of antennas:

- DAR antennas as transmitter
- Shielded loop antennas as receiver

A DAR-antennas, and a shielded loops have been manufactured at TDF.

#### 3) Transmitters: DAR-antennas

The transmitting antenna, based on a patented surface-waves antenna, called DAR antenna [12], has been optimized, realized, and installed in salt ponds (see Fig. 5). The antenna is manufactured with a steel galvanized wire with a diameter of 2.7 mm. The dimensions have been adjusted according to the selected frequency. The length  $L_t$  is equal to 20.4 meters; the vertical height  $h$  is 1.8 meters with a gap  $Z_e$  of 0.5 meters.

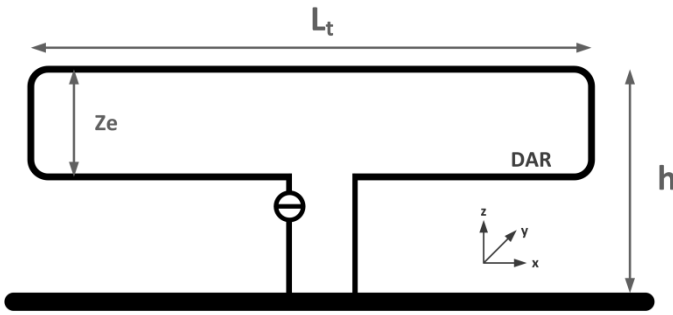


Fig. 5. DAR-antenna design and tuning parameters: horizontal length ( $L_t$ ), vertical gap ( $Z_e$ ), and vertical height ( $h$ ).

The horizontal radiation patterns are omnidirectional, and the vertical radiation pattern is quite similar to a monopole over an extremely good conductor. The antenna gain has been measured in the relevant azimuth in order to calculate the radiated electric field strength. The antenna gain at 5 MHz is -3.8 dBi. The input power is 45 dBm.

#### 4) Receivers: Shielded-loop antennas

The receiving antennas are narrow-band shielded-loops. The frequency selectivity and the shield have been used in order to improve the signal to noise ratio (SNR), especially when the measurement distance increases.

Generally, the shield takes the form of a tube around the wire, made of conductive but nonmagnetic material (such as copper or aluminum). Antennas have been manufactured with flexible coaxial cables (see **Erreur ! Source du renvoi introuvable.**). The inner copper conductor (1) is the power fed element and the outer copper conductor (3) is the shield.



Fig. 6. Coaxial cable design: inner copper conductor (1), dielectric (2), outer copper conductor (3) and outer jacket (4).

Fig. 7 sketched the shielded-loop design and their tuning parameters (loop diameter  $d_L$ , variable air capacitors  $C$ ). Usually, the insulated break is located in the opposite side of the feed point to maintain the symmetry. Baluns have been realized in order to maintain loop balance and to match the impedance of the antenna to 50  $\Omega$ . It is important to consider the effect of the antenna shield because, by using a flexible coaxial cable, some additional capacitive components have been involved. This loop design limits the loop's higher frequency tuning range with a fixed diameter  $d_L$ . As a result, the antenna configuration has been optimized according to the frequency. At 5 MHz, a 1''5/8 coaxial cable has been used to manufacture a loop with a diameter  $d_L$  of 1.05 meters. Then, the frequency tuning is realized manually with variable air capacitors  $C$  controlled by a network analyzer.

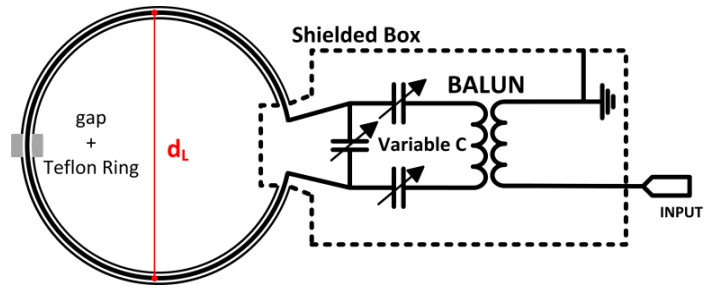


Fig. 7. Shielded-loop design and tuning parameters: diameter  $d_L$ , variable capacitors  $C$ .

It is useful in field strength measurements to characterize the receiving antenna by its conversion factor  $K_a$  as well as by the antenna gain. The relationship between them is described here. The electrical field  $E$  is derived from the measured voltage  $U$  and the conversion factor  $K_a$  of the antenna:

$$E_{dB\mu V/m} = U_{dB\mu V} + K_{a,dB} \quad (19)$$

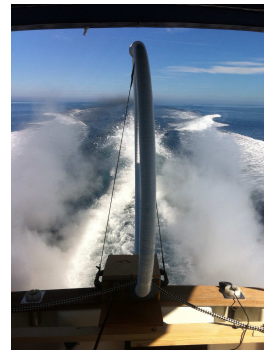


Fig. 8. Realized shielded-loops, installed on the boat.

The antenna bandwidths at 5 MHz is 0.4% at -3 dB. The  $K_a$ -

factor is inversely proportional to the gain. So, the lower

the K-factor, the higher the efficiency. The realized

shielded-loop antennas are tested to measure the radiation

- Shielded-loop antennas realized in order to

efficiency thanks to:

measure the voltage  $U$

- Receiver ESH3 (from Rhode & Schwarz) which is

able to measure an electrical field and a voltage.

- A broadband transmitter

- A calibrated active loop antenna (from Rhode &

Schwarz [13]) in order to measure the electrical

So, the radiation efficiencies (written in the form of K-

field  $E$

factor) is 10 dB/m at 5 MHz. As a result, the selective

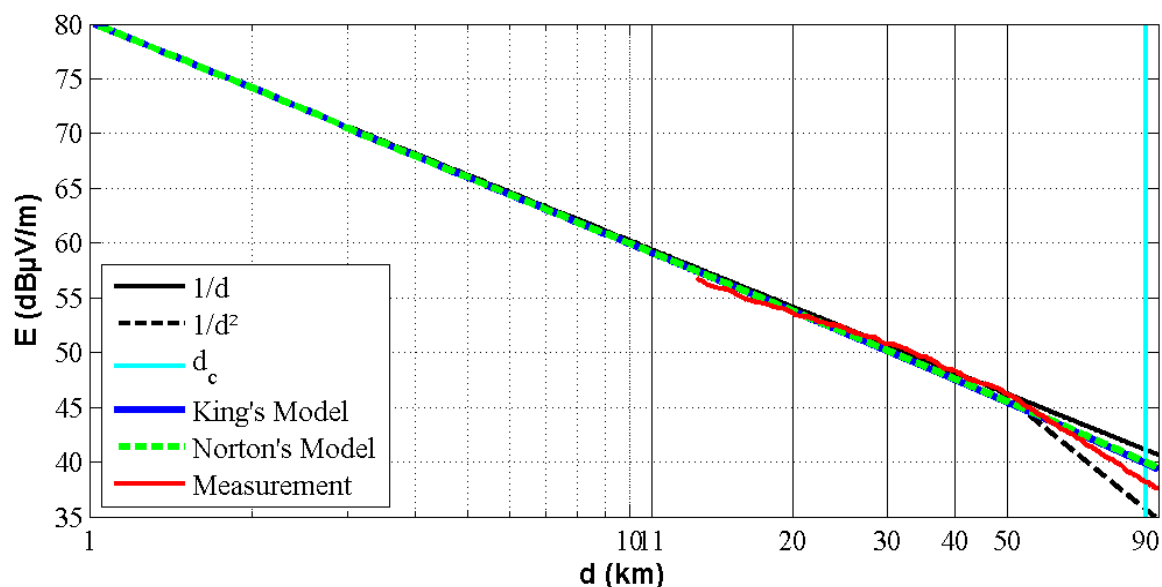


Fig. 9. Theoretical and measured Electric field attenuation at 5 MHz over a mixed path: marsh and sea water. The theoretical results are calculated from Norton's and King's models. The Millington's solution is considered over the mixed path in order to take into account the environmental constraints. The red curve represents the measurements over the sea water.

shielded-loop antennas allow to increase the measurement

sensitivity around 30 dB compared with a broadband loop

antenna. This improvement was necessary for the far-

away measurements.

#### IV. COMPARISON BETWEEN MEASUREMENTS AND THEORETICAL CALCULATION.

Fig. 9 presents the theoretical and the measured Electric field along a 90 km mixed-path (salt pond, mudflat and sea water) at 5 MHz. 11 points per kilometers have been recorded. The theoretical models (King and Norton) and the measurement results are in good agreement. The maximal discrepancy between measured data and theoretical models is 2 dB. The average error is less than 1 dB. The average deviation error is around to 0.45 dB. The EM field attenuation slope is the  $1/d$  attenuation as predicted by the characteristic distances of King. It appears that around the critical distance  $d_c$  (planar Earth model boundary), the slope of the measured and theoretical data tends to change smoothly from the  $1/d$  variation but don't reach the  $1/d^2$  variation (see black curves on Fig. 9). Further, the topography has optimum electrical characteristics along the three mixed paths with salt ponds (very high conductivity), mudflat (good conductivity), and sea water (high conductivity). At 5 MHz, this mixed path has not a visible effect on the propagation curves, but has to be considered to respect the topography of the measurement area.

#### I. CONCLUSION

In this paper, the measurement of surface waves propagating along sea water path in the HF band at 5 MHz is compared with theories. First of all, we have described briefly the theoretical results proposed by Norton, King, and Millington. Then, we have presented measurement results at 5 MHz and

compared it to the theories including Millington's modification in order to take into account the interface between the coast and water sea. At 5 MHz, the  $1/d$  attenuation is shown and is very well correlated with the theory.

A future work is scheduled to measure the electric field strength of the surface wave at larger distances and at other frequencies in order to consider the roundness of the Earth.

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